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TITLE: LOW RISK LOW POWER HEAT PIPE/THERMOELECTRIC SPACE POWER SUPPLY

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LOW RISK LOW POWER HEAT PIPE/THERMOELECTRIC SPACE POWER SUPPLY

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INTRODUCTION

In recent years there has arisen a general assumption in the U. S. space power community that nuclear reactors should not be considered for space applications in the power range below 5 kWe. This is despite the fact that the only space reactor the U. S. has ever flown and all but two of the several dozen reactors flown by the USSR have had power outputs well under 5 kWe. It appears to be taken as a given that, at low power, reactors are competitive in terms of mass with neither solar power supplies, even if hardened, nor isotope power supplies. Recently released information on the reactor powering the USSR Cosmos 1900 satellite makes it clear that relatively lightweight low power reactor designs are not only possible, but are, in fact, in orbital operation (Stepnoi 1989). Remaining questions revolve around whether the low mass feature can be retained as the power supply lifetime is increased to the order of 5 - 10 years and whether reliability, survivability, and cost can also match or top solar and isotope power supplies.

This paper discusses guidelines directed towards achieving low mass reactor power systems and describes a system that combines features - a number borrowed from earlier concepts - that reduce mass at the same time as they reduce development risk and increase reliability.

DESIGN CONSIDERATIONS

It is obvious that the main consideration in attempting to produce a low mass reactor design is to keep the reactor volume as small as possible. This is not only to keep the core and reflector mass down, but also to reduce the required shield diameter to a minimum. Because heat removal at low power is not a limiting factor on size reduction, overall mass reduction favors a high fuel density fast spectrum core. This was achieved in the USSR system referred to above by using metallic uranium fuel to achieve a very compact core. However, this approach severely limits the operating temperature of core, and, as the desired system power output is increased, rapidly becomes a lifetime limiting approach as well. Thus, uranium nitride and uranium carbide, though having only 71% and 68%, respectively, of the uranium density of the metal, are nevertheless more desirable as fuel materials. Given the maximum feasible fuel density core compactness can be further increased by reducing fuel cladding as much as possible and by avoiding waste space associated with traditional cylindrical fuel elements. Both of these approaches are feasible for low power systems because of the very low power density in the fuel.

Another means of reducing reactor system mass is to reduce the diameter of the shield, especially the gamma shield, by moving it as close to the reactor core as possible, even to the extent of having the gamma shield serve as a heavy metal end-reflector. Tapering the reflector and control segments, also leads to shield diameter reduction. Replacement of tungsten with lead oxide is another potential means of achieving shield mass reduction because it avoids the problem of seconday gamma ray production in the shield.

The mass of the heat transfer/power conversion system can be substantially reduced if pumped loops and heat exchangers can be eliminated. This can be done without incurring appreciable technical risk by using a combination of heat pipe reactor heat removal and thermoelectric converters. In addition to the mass reduction potential the heat pipe thermoelectric approach also promises reliability and the avoidance of single point failure mechanisms, freedom from vibration, and scalability.

LOW RISK REACTOR POWER SYSTEM DESIGN (ALERT)

The low power space reactor system that resulted from an effort to generate reactor power supplies competitive with hardened solar and isotope power supplies features a very compact core of uranium carbide fuel penetrated by Nb1%Zr/Na heat pipes. These heat pipes pass through the reactor shield and deliver reactor heat to thermoelectric unicouples that are brazed directly to them. Waste heat removal is accomplished by heat pipe assisted beryllium fins mounted directly to the cold junctions of the unicouples. The configuration of the reactor core is shown in Fig. 1. Eighteen heat pipes are welded into an open Nb1%Zr core can as seen at the top of the figure These are coated with a very thin plasma-sprayed layer of tungsten to prevent any reaction of the niobium heat pipe wall with the uranium carbide fuel. Between ten and fifteen plates of uranium carbide, with holes in the appropriate locations, as shown in Fig. 2, are slipped over the heat pipe array, one at a time, and dense carbon wool packing is tamped into the narrow gaps between the heat pipes and the fuel plates in order to guarantee good thermal contact. The core has a central control rod to provide an alternative shutdown method and also to guarantee subcriticality in the event the reactor, including heat pipes, is flooded with water. The primary control system features rotatable Be drums with boron carbide segments mounted in the Be reflector.

Fig. 3 shows the overall configuration of the power system. The gamma shield is placed as close to the core as possible so that it plays the role of one end reflector. The shield material may be tungsten, ZrH, or a PbO/Be cermet. The core heat pipes pass through and around the gamma and LiH neutron shields and, at the base of the latter, flare out into a conical array. It is in this region that the thermoelectric unicouples are brazed to the heat pipes. The Be fins attached to the cold shoes of each unicouple form the radiator surface shown in the figure. Because the fins can radiate heat from their inner as well as their outer surfaces, there is no advantage to filling the gaps between adjacent heat pipe/TE converter sets. However, a space is left at the base of the conical radiator and a contoured IR reflector is provided to take full advantage of the heat radiation capability of the inner fin surfaces.

The manner in which the unicoupole assemblies are joined to the heat pipes is illustrate in Fig. 4. Here the heat pipe is shown with a D-shaped cross section with a unicouple brazed to the flat side. The unicouple component stack is assembled by a combination of brazes and diffusion bonding steps, all of which have been demonstrated as part of the SP-100 advanced development program. The overall configuration is very similar to that used and successfully launched in the SNAP-10A program. Besides the use of heat pipes rather than pumped liquid metal loops (with their attendant temperature drops), the main changes from the SNAP-10A arrangement are the transition to niobium, higher temperature brazes, and the use of a platinum stress relieving washer instead of the gold used in the earlier program.

DEVELOPMENT RISK REDUCTION FEATURES

The general approach in reducing the development risk associated with the ALERT system is to reduce the high side temperature approximately 200 K relative to isotope powered RTG technology and to the technology currently being developed for the SP-100 program. This temperature reduction has several beneficial effects. It greatly reduces concern with the fuel relative to fission gas induced swelling and fission gas release. Coupled with the low burnup requirement for electrical powers in the range of 1 to 10 kWe, predictions based on existing irradiation data are that less than 1 % fuel swelling and less than 1 % fission gas release will occur in 10 y operating time. The temperature reduction also makes it possible to dispense with lithium as the coolant and brings the operating regime to a temperature where a considerable amount of favorable long term experience has been gained on niobium heat pipes with sodium working fluid. It is within 100 K of the temperature regime where a great deal of successful fast neutron irradiation experience has been obtained on stainless steel heat pipes with sodium working fluid.

The elimination of lithium as a coolant in conjunction with the reduction in temperature essentially eliminates the potential problem of stable insulator operation in an electric field at elevated temperature, primarily because there will be no tendency for sodium to strip oxygen from the insulator material as is the case for lithium. The lower operating temperature further reduces any risk of insulator degradation. It also lowers the risks involved in the unicouple design although the brazes and materials for these units are expected to be stable for multiyear operation even at the 1350 K level associated with SP-100 and RTGs.

SYSTEM PARAMETERS

Table 1 lists the system parameters for an ALERT configuration designed to produce 2 kWe of raw power at 28 V d.c.. The component masses for this system are given in Table 2. It can be seen that the shield is the major contributor to the system mass. This is because the payload was assumed to be only 5 m from the front surface of the reactor core and the shield half angle was taken to be 15°. Shield mass could be substantially reduced by separating the reactor from the payload by a long flexible boom, but this would greatly reduce the applicability of the unit.

The reactor masses given in Table 2 are based on MCNP criticality calculations giving a k_{eff} of 1.05. Actual Control and Instrumentation masses will depend greatly on safety constraints and the estimates given here are probably optimistic. Power conditioning requirements are so user dependent that mass estimates have not been included in the power system totals.

TABLE 1

SYSTEM PARAMETERS
2kWe ALERT POWER SYSTEM

COOLANT TEMPERATURE	1125 K
POWER DENSITY IN FUEL	20 W/CM^3
RADIATOR TEMPERATURE	775 K
CONVERSION EFFICIENCY	3.5 %
NO. OF COOLANT CHANNELS	18
POWER PER COOLANT CHANNEL	3.2 KWT
SHIELDING (10 Y EXPOSURE AT 5 M, 15° HALF ANGLE):	
GAMMA	5 X 10^5 RAD
NEUTRON	5 X 10^{12} N/CM^2

TABLE 2

SYSTEM MASSES
2kWe ALERT POWER SYSTEM
(kg)

CORE	40	HEAT TRANSPORT	35	SHIELD:	
REFLECTOR	35	TE CONVERTERS	20	GAMMA	80
CONTROL	15	(INCLUDING RADIATOR)		NEUTRON	145
INSTRUMENTATION	15				
REACTOR TOTAL	105	CONVERSION TOTAL	55	SHIELD TOTAL	225

STRUCTURAL ELEMENTS: 20

SYSTEM TOTAL: 405kg (without power conditioning)

SCALABILITY

Design studies have been performed on the ALERT system for a range of power from 1 kWe to 30 kWe. System mass estimates for various power levels are given in table 3. While this table shows that very competitive mass values are obtained over the entire range of power, the concept is particularly attractive for power levels of 10 kWe and below. In this power range comparative studies have shown that it is substantially less massive than any other technically feasible reactor power system (Space Reactor Panel 1988). This is despite the fact that temperature derating to achieve low development risk has substantially reduced the potential system performance. Were the risk factors equivalent to current reactor development programs to be used in the ALERT system substantial increases in performance with accompanying mass reductions would be possible.

TABLE 3

SCALABILITY OF ALERT POWER SYSTEM

POWER - kWe	MASS - kg
1	330
2	405
6	600
10	903
30	1800

DISCUSSION

The ALERT power system combines established thermoelectric, heat pipe, and nuclear fuel technology into a compact and low mass nuclear power system that features low development risk, avoidance of pumped coolant loops and heat exchangers, high redundancy, and general simplicity of design. The estimated masses for various power levels in the 1 to 10 kWe range are competitive with current solar power supply technology and highly competitive with projected hardened solar power supplies. They are also very competitive with projected isotope power supply masses. The ALERT system has a number of other advantages relative to either solar or isotope systems or both. Relative to solar the advantages include the attainment of high performance without requiring gimballing mechanisms to achieve constant solar pointing, an inherently hardened structure and the capability for use in outer planet exploration missions. Relative to isotope power supplies some advantages are unit cost and the avoidance of vibrations associated with dynamic conversion machinery.

ACKNOWLEDGMENTS

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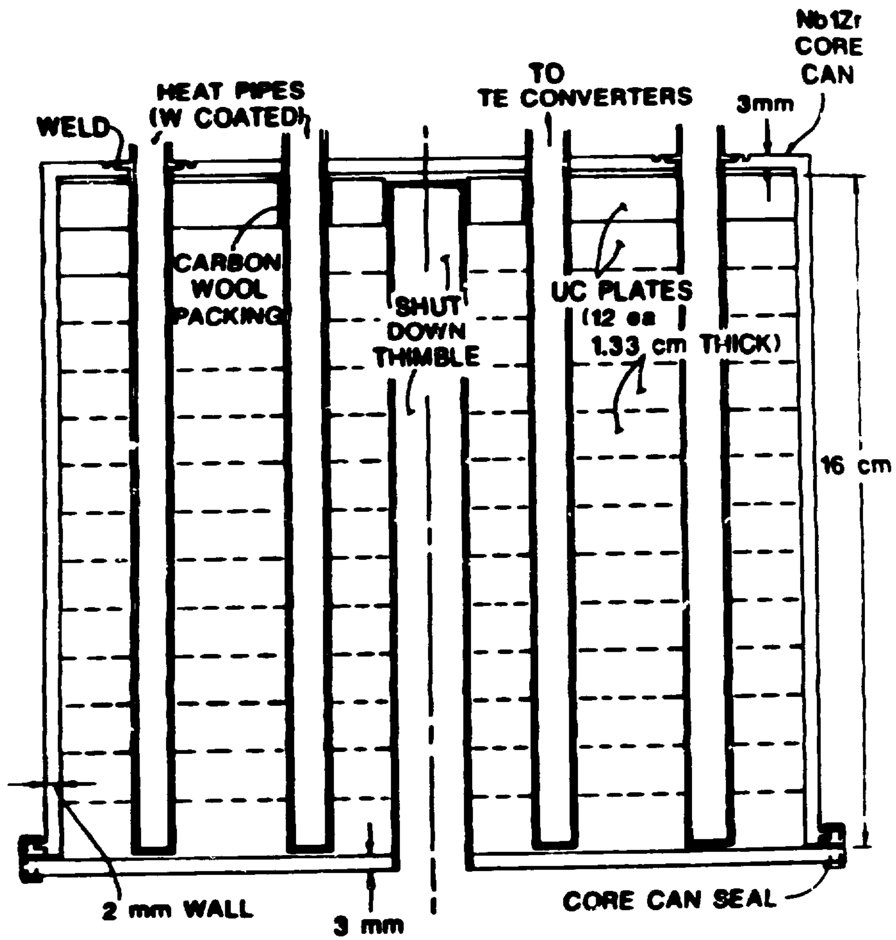

Figure 1. Side View of 2 kWe ALERT Reactor Core Configuration.

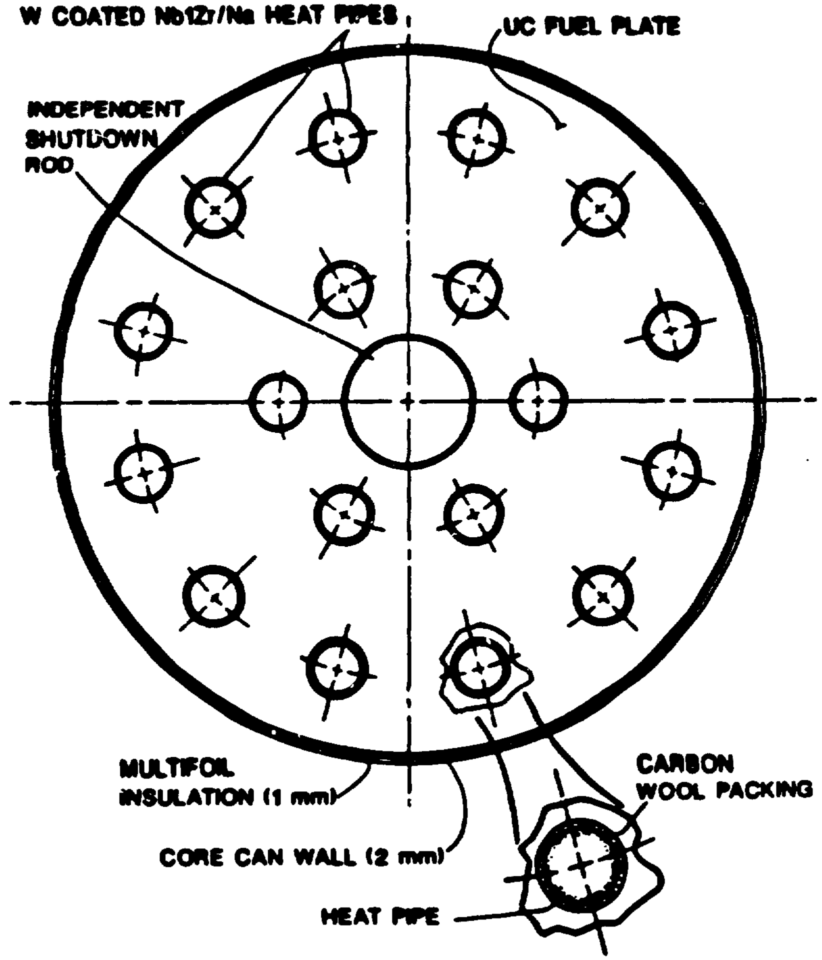

Figure 2. Top View of 2 kWe ALERT Reactor Core Configuation.

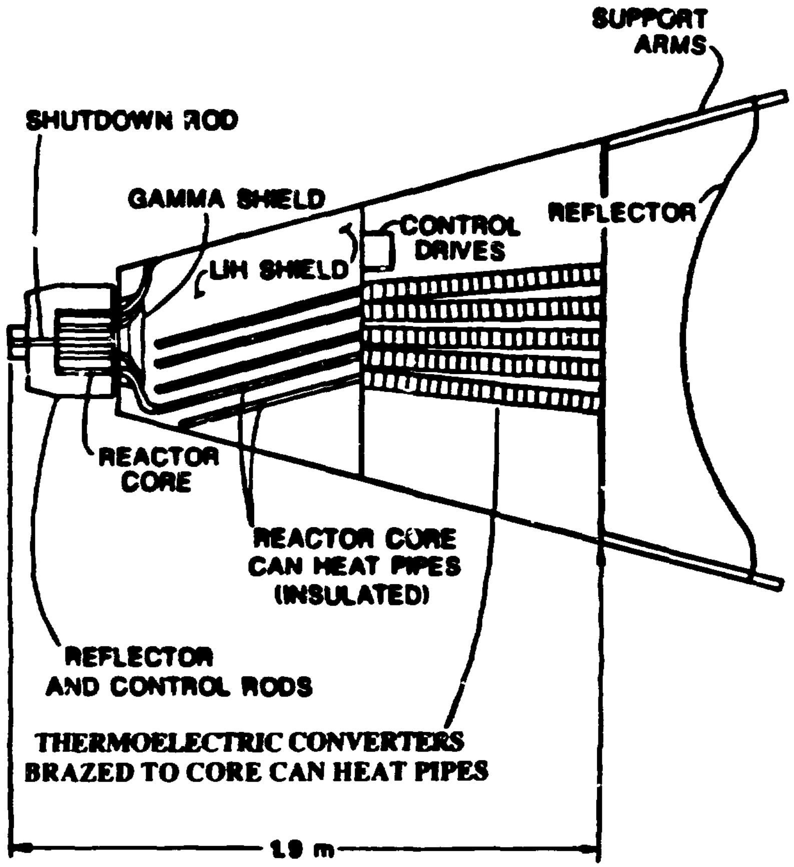

Figure 3. 2 kWe ALERT System Configuration.

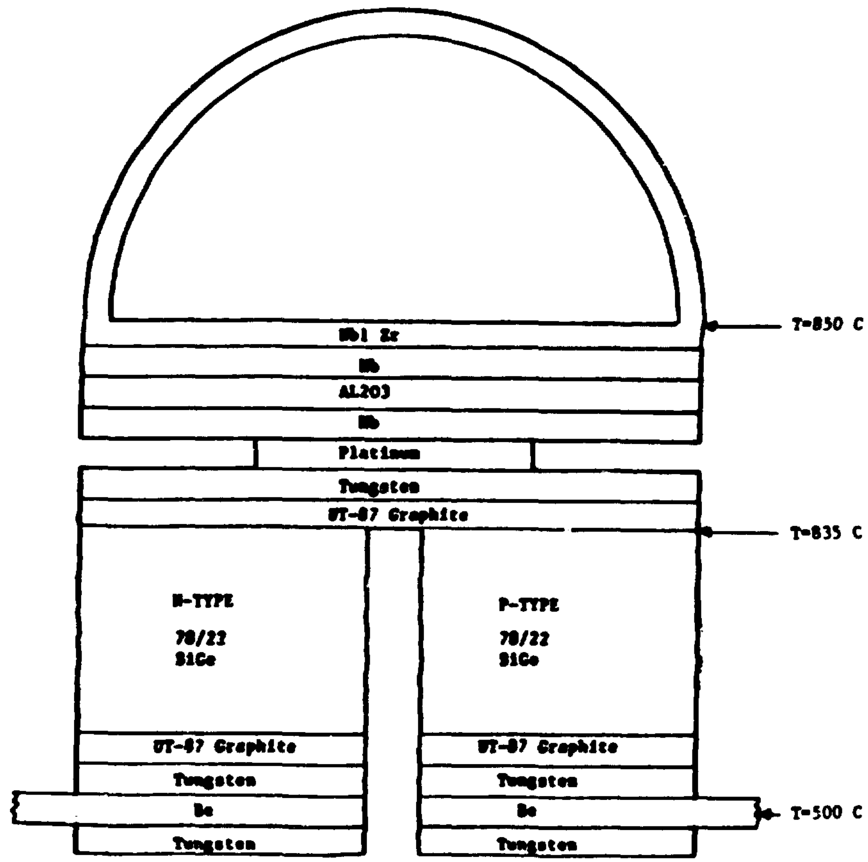

Figure 4. Unicouple Assembly Shown Brazed to D-Cross Section Heat Pipe.